13th International Brick and
Block Masonry Conference
Amsterdam, July 4-7, 2004

SIMPLIFIED DESIGN MODEL FOR REINFORCED MASONRY

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Abstract

In regard to an economic design of reinforced masonry two new simplified design models have been developed. Hereby the varying non-linear material behavior of different masonry types is being considered by easy-to-use equations. The simplified method for the approximation of lateral wall deformation according to theory of 2nd order is based on the theoretical model used for the design of reinforced concrete. Furthermore analytical equations for the dimensioning of the required reinforcement of masonry structures are being presented. Accordingly design diagrams and design tables are not needed any more in future. In consideration of an easy application of the new methods the design of a reinforced masonry beam and a reinforced basement wall is shown.

Key Words

reinforced masonry, required reinforcement, simplified design, non-linear

1 Introduction

In Germany reinforced masonry is not as common as in other European countries today. Due to the advantages of reinforcing masonry structures this is likely to change in future. Reinforcement does not only increase the masonry's load-bearing capacity but also enhances it's serviceability, e.g. reduced crack initiation. Furthermore the latest redrafts of German and European standards concerning wind and earthquake design propose increased loads for some German regions. Due to higher lateral loading reinforcement will be necessary more often. Accordingly the out-of-date design methods of DIN 1053-3:1990 have to be replaced by new methods which meet the latest technical standards.
Considering the similarity of reinforced masonry and reinforced concrete two new simplified design models have been developed in Darmstadt on the basis of the varying non-linear material behavior of different masonry types (Graubner and Glock 2004, Glock and Graubner 2002). The simplified concept for the approximation of lateral wall

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deformation according to theory of 2nd order has been based on DIN 1045-1:2001 and Eurocode 2 (DIN V ENV 1992-1-1:1992) for reinforced concrete. The new dimensioning method for the required reinforcement of masonry structures is based on the non-linear stress distribution in the cross section depending on the provided masonry type. Hereby the reinforcement can be calculated on the basis of easy-to-use equations. Consequently design diagrams and design tables are unnecessary. Due to the general approach the new design methods guarantee the consistency of concrete and masonry design. Their application to reinforced concrete is possible, too. The use of the new methods is shown for the design of a reinforced masonry beam and a reinforced masonry basement wall.

2 Lateral wall deformation according to theory of 2nd order

2.1 General

Due to the dependence of lateral wall deformation and acting bending moment the structural analysis of slender walls has to consider effects according to theory of 2nd order. Hereby the complex non-linear analysis is usually replaced by simplified methods in various design standards where the additional load eccentricity according to lateral wall deformation Δe_{II} and the imperfection e_a is being approximated. Accordingly the design of slender walls then can be simplified as a proof of the load-bearing capacity of the cross section in the middle part of the wall on the basis of the total bending moment $M_{II}=N \cdot e_{II}$:

$$e_{II} = e_I + e_a + \Delta e_{II} \tag{1}$$

e_I load eccentricity according to theory of 1st order
e_a load eccentricity according to geometrical imperfections
Δe_{II} additional load eccentricity according to theory of 2nd order

2.2 DIN 1053-3 and Eurocode 6

DIN 1053-3:1990 proposes a simplified equation for the approximation of Δe_{II} for common wall slenderness ratios ($h_{ef}/t \leq 20$). In case of $20 < h_{ef}/t \leq 25$ DIN 1045:1988 for reinforced concrete has to be applied. According to DIN 1053-3 the load eccentricity e_{II} in the middle third of the wall is determined for $e_a + \Delta e_{II}$, where $e_a = h_{ef}/300$.

$$e_{II} = e_I + e_a + \Delta e_{II} = e_I + \frac{h_{ef}}{46} - \frac{t}{8} \tag{2}$$

h_{ef} effective height of the wall considering the buckling length factor
t wall thickness

The latest redraft auf Eurocode 6 (prEN 1996-1-1:2003) limits the maximum wall slenderness to $h_{ef}/t \leq 27$. The load eccentricity according to geometrical imperfection is determined by $e_a = h_{ef}/450$. The total load eccentricity then is:

$$e_{II} = e_I + e_a + \Delta e_{II} = e_I + \frac{h_{ef}}{450} + \frac{1}{2000} \cdot \frac{h_{ef}^{\;2}}{t} \tag{3}$$

2.3 Simplified approximation method

A simplified approximation method for the lateral wall deformation according to theory of 2nd order has been developed for reinforced masonry walls (Graubner and Glock 2004, Glock and Graubner 2002) on the basis of Kordina and Quast (2002). Due to the

ongoing discussion about strain limitation in German standardization committees the simplified equations are formulated as a function of the reinforcement's and masonry's ultimate strain. Accordingly the additional load eccentricity Δe_{II} is:

$$\Delta e_{II} = \frac{1}{10} \cdot \left(\frac{1}{r}\right) \cdot h_{ef}^{\ 2} \qquad \text{with } \left(\frac{1}{r}\right) \approx \frac{\left|\varepsilon_{s,\max}\right| + \left|\varepsilon_u\right|}{d} \tag{4}$$

d	effective depth of the cross section
$\varepsilon_{s,max}$	maximum tolerated strain of reinforcement or yield strain if $\varepsilon_{s,max}>\varepsilon_{yk}$
ε_u	maximum strain of masonry

In case of limiting the reinforcement's strain to the yield strain $\varepsilon_{s,max}=\varepsilon_{yk}=2.5‰$ if $f_{yk}=500\text{N/mm}^2$ and the maximum masonry compression to $|\varepsilon_u|=2.0‰$ the critical curvature ($1/r$) of the cross section is illustrated in Figure 1. The additional load eccentricity according to lateral wall deformation then is:

$$\Delta e_{II} = \frac{1}{2200} \cdot \frac{h_{ef}^{\ 2}}{d} \tag{5}$$

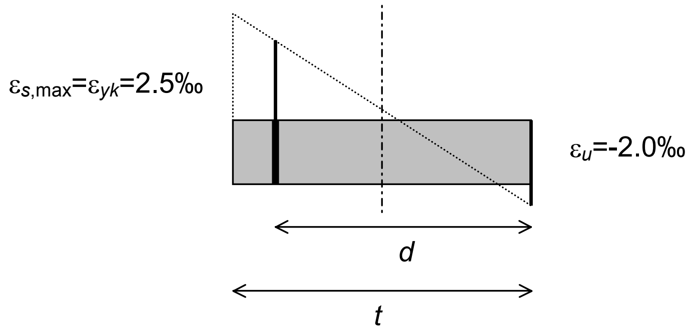

Figure 1 Critical curvature (1/r) of the cross section

Considering the partial safety factor $\gamma_s=1.15$ for reinforcement, the maximum yield strain has to be limited to $\varepsilon_{yd}=2.5/1.15=2.17‰$ for wall design. The ultimate strain of compressed masonry has to regard the provided masonry type. In case of masonry with $|\varepsilon_u|=2.0‰$ (e.g. clay or vertically perforated calcium silicate bricks) Δe_{II} is:

$$\Delta e_{II} = \frac{1}{2400} \cdot \frac{h_{ef}^{\ 2}}{d} \qquad (\text{for } |\varepsilon_u|=2.0‰) \tag{6}$$

In case of $|\varepsilon_u|=3.5‰$ (e.g. solid calcium silicate bricks) Δe_{II} is:

$$\Delta e_{II} = \frac{1}{1750} \cdot \frac{h_{ef}^{\ 2}}{d} \qquad (\text{for } |\varepsilon_u|=3.5‰) \tag{7}$$

If the presented approximation methods are compared, two main differences turn out. While the load eccentricity according to geometric imperfection e_a is determined independently of Δe_{II} in Eurocode 6 and the new simplified method, DIN 1053-3:1990 (Eq. (2)) considers a fixed load eccentricity $e_a=h_{ef}/300$. Furthermore the additional load eccentricity Δe_{II} according to DIN 1053-1:1990 and Eurocode 6 has to be calculated as a function of the effective height h_{ef} and the wall thickness t. In contrast the new concept considers the effective depth d of reinforced masonry walls.
Figure 2 exemplarily shows the comparison of the load eccentricity $e_a+\Delta e_{II}$ on the basis of a uniformly geometric imperfection $e_a=h_{ef}/300$ for DIN 1053-3, Eurocode 6 and the new concept according to Equation (5). Hereby the effective depth is varied between the border case $d/t=1.0$ and $d/t=0.5$ for centric reinforcement according to Equation (5).

The significant influence of the ratio *d/t* to the additional load eccentricity Δe_{II} points out the importance of it's consideration for the design of masonry walls.

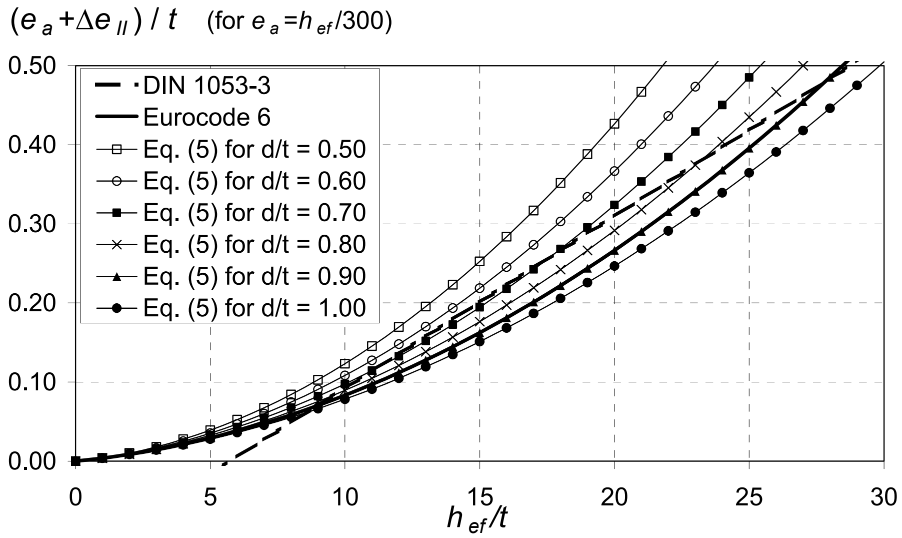

Figure 2 Load eccentricity $e_a+\Delta e_{II}$ according to different approximation methods

3 Required Reinforcement

3.1 General

Currently the required reinforcement of masonry and concrete structures is determined on the basis of design tables and design diagrams, which are provided for varying material behavior. In contrast the new design method (Graubner and Glock 2004, Glock and Graubner 2002) makes possible the analytical calculation of the required reinforcement of asymmetrically reinforced masonry and concrete structures. Hereby the reinforcement can be calculated as a function of the bending moment, the axial load, the geometric parameters and the material properties of the provided masonry type. In addition design diagrams and design tables can be generated, too.

3.2 Analytical dimensioning method

The required reinforcement of masonry structures is determined by the equilibrium conditions for the cross section. Hereby the stress-strain relationship of the reinforcement can be assumed as linearly elastic with a constant stress for strains greater than the yield strain. In contrast the material behavior of masonry depends on the provided masonry units and the mortar type. According to DIN 1053-3:1990 a parabolic stress-strain relationship is assumed. The latest redraft of Eurocode 6 (prEN 1996-1-1:2003) differentiates between a linear, parabolic, parabolic-rectangular and rectangular stress-strain relationship. Considering the varying material behavior of masonry the new dimensioning method is formulated in a general way. Accordingly the required reinforcement can be calculated for any masonry type and concrete. Hereby the axial load and the bending moment have to be standardized according to Figure 3:

$$n_{sd} = \frac{N_{sd}}{b \cdot d \cdot f_d} \qquad \text{(N_{sd} is positive for compression load)} \qquad (8)$$

$$m_{sds} = \frac{M_{sd}}{b \cdot d^2 \cdot f_d} + n_{sd} \cdot \left(1 - \frac{t}{2 \cdot d}\right) \qquad (9)$$

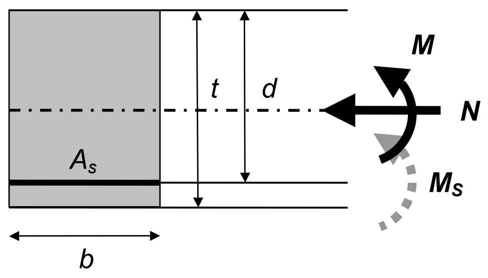

Figure 3 Cross section with asymmetrical reinforcement

The specific material behavior of any masonry type is being considered by:

$$\delta = \frac{2 \cdot k_a}{\alpha_R} \qquad \bar{\varepsilon}_y = \left|\frac{\varepsilon_{yd}}{\varepsilon_u}\right| \qquad \bar{\varepsilon}_u = \left|\frac{\varepsilon_{s,\max}}{\varepsilon_u}\right| \tag{10}$$

δ	parameter describing the stress-strain relationship for compression:	
	constant:	δ=1.0
	parabolic-rectangular (as for concrete):	δ=1.03≈1.0
	parabolic:	δ=1.125
	linearly elastic:	δ=1.333
α_R	ratio of resulting axial force compared to constant stress $\sigma=f$	
k_a	standardized location of resulting axial force	
f_d	compressive strength of masonry ($f_d=f_k/\gamma_m$)	
ε_u	ultimate strain of masonry	
ε_{yd}	design yield strain of reinforcement	
$\varepsilon_{s,max}$	maximum tolerated strain of reinforcement	

According to the equilibrium conditions the required reinforcement area A_S is defined as a function of the standardized loads m_{sds} and n_{sd} and the material parameters:

$$\text{req } A_s = \omega_{1,2} \cdot b \cdot d \cdot \frac{f_d}{f_{yd}} \tag{11}$$

$$\bar{\omega} = 1 - \sqrt{1 - 2 \cdot \delta \cdot m_{sds}} \tag{12}$$

$$\omega_1 = \frac{\bar{\omega}}{\delta} - n_{sd} \qquad \text{for } \bar{\omega} \le \frac{2 \cdot k_a}{\bar{\varepsilon}_y + 1} \qquad \text{with } \varepsilon_s \ge \varepsilon_{yd} \tag{13}$$

$$\omega_2 = \frac{\bar{\varepsilon}_y \cdot \bar{\omega}}{2 \cdot k_a - \bar{\omega}} \cdot \omega_1 \qquad \text{for } \frac{2 \cdot k_a}{\bar{\varepsilon}_y + 1} < \bar{\omega} \le 2 \cdot k_a \qquad \text{with } 0 \le \varepsilon_s < \varepsilon_{yd} \tag{14}$$

For small axial compression loads the reinforcement's strain usually is greater than the yield strain ε_{yd}, especially when considering reinforced concrete. In this case Equation (12)-(13) have to be applied. Due to the strict strain limitations for masonry the computed strain of the reinforcement according to the simplified design equations occasionally is greater than the tolerable strain ($\varepsilon_s>\varepsilon_{s,\max}$ for $\bar{\omega}<2\cdot k_a/(\bar{\varepsilon}_u+1)$). In this case Equation (13) is not exact any more, but the discrepancies to the exact result is smaller than 6%. In case of $\varepsilon_s<\varepsilon_{yd}$ Equation (14) has to be applied.
In terms of an easy application of the new design method the general Equations (12)-(14) are being analyzed for the specific material behavior of different masonry types according to Eurocode 6. As a lower limit a linearly elastic stress-strain relationship is being assumed for compressed masonry. According to the partial safety factor of

reinforcement the design yield strain is ε_{yd}=f_{yk}/(E·γ_s)=500/(200.000·1.15)=2.17‰. The material parameters of masonry are: |ε_u|=2.0‰, α_R=1/2 and k_a=1/3. Considering these material properties the required reinforcement can be calculated on the basis of Equation (11) and the standardized reinforcement ratios ω_1 and ω_2:

$$\overline{\omega} = 1 - \sqrt{1 - \frac{8}{3} \cdot m_{sds}} \qquad (15)$$

$$\omega_1 = \frac{3}{4} \cdot \overline{\omega} - n_{sd} \qquad \text{for } \overline{\omega} \le \frac{1}{3} \qquad (16)$$

$$\omega_2 = \frac{10 \cdot \overline{\omega}}{6 - 9 \cdot \overline{\omega}} \cdot \omega_1 \qquad \text{for } \frac{1}{3} < \overline{\omega} \le \frac{2}{3} \qquad (17)$$

In case of a parabolic stress-strain relationship of compressed masonry the dimensioning equations have to be based on the specific material parameters |ε_u|=2.0‰, α_R=2/3 and k_a=3/8. Hereby the standardized reinforcement area is:

$$\overline{\omega} = 1 - \sqrt{1 - 2.25 \cdot m_{sds}} \qquad (18)$$

$$\omega_1 = \frac{8}{9} \cdot \overline{\omega} - n_{sd} \qquad \text{for } \overline{\omega} \le \frac{3}{8} \qquad (19)$$

$$\omega_2 = \frac{13 \cdot \overline{\omega}}{9 - 12 \cdot \overline{\omega}} \cdot \omega_1 \qquad \text{for } \frac{3}{8} < \overline{\omega} \le \frac{3}{4} \qquad (20)$$

If the stress-strain relationship of masonry is assumed to be parabolic-rectangular the following equations are valid for reinforced concrete, too. The idealization of the load deformation behavior by a parabolic curve for |ε|≤2.0‰ and a constant stress for 2.0‰<|ε|≤3.5‰ is also used in DIN 1045-1:2001 and Eurocode 2. Herby the specific material parameters are |ε_u|=3.5‰, α_R=0.81 and k_a=0.42:

$$\overline{\omega} = 1 - \sqrt{1 - 2 \cdot m_{sds}} \qquad (21)$$

$$\omega_1 = \overline{\omega} - n_{sd} \qquad \text{for } \overline{\omega} \le 0{,}5 \qquad (22)$$

$$\omega_2 = \frac{3 \cdot \overline{\omega}}{4 - 5 \cdot \overline{\omega}} \cdot \omega_1 \qquad \text{for } 0.5 < \overline{\omega} \le 0.8 \qquad (23)$$

Exemplarily Figure 4 and 5 show design diagrams for the required reinforcement on the basis of a linearly elastic and a parabolic-rectangular stress-strain relationship of masonry for a effective depth of d=0.9·t. These diagrams are based on the new dimensioning concept. The influence of varying material behavior can be seen when comparing the design diagrams. For the standardized reinforcement area ω=0.3 and the axial load n_{sd}=0.1 the resulting standardized bending moment is m_{sd}=0.19. In case of a parabolic-rectangular idealization of the material behavior the bending moment is m_{sd}=0.27. Regarding the wide range of m_{sd} for different stress-strain relationships the material behavior has to be considered for the dimensioning of reinforcement.

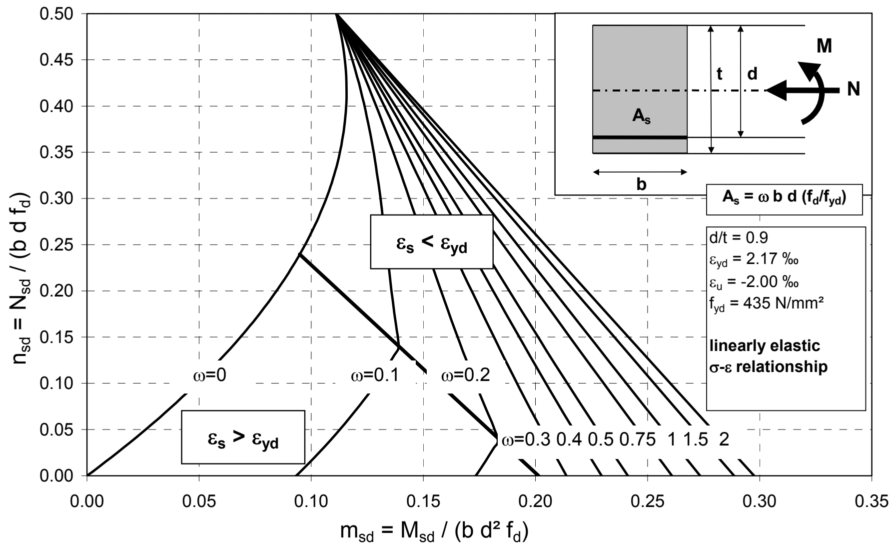

Figure 4 Design diagram for d/t=0.9 and linearly elastic material behavior

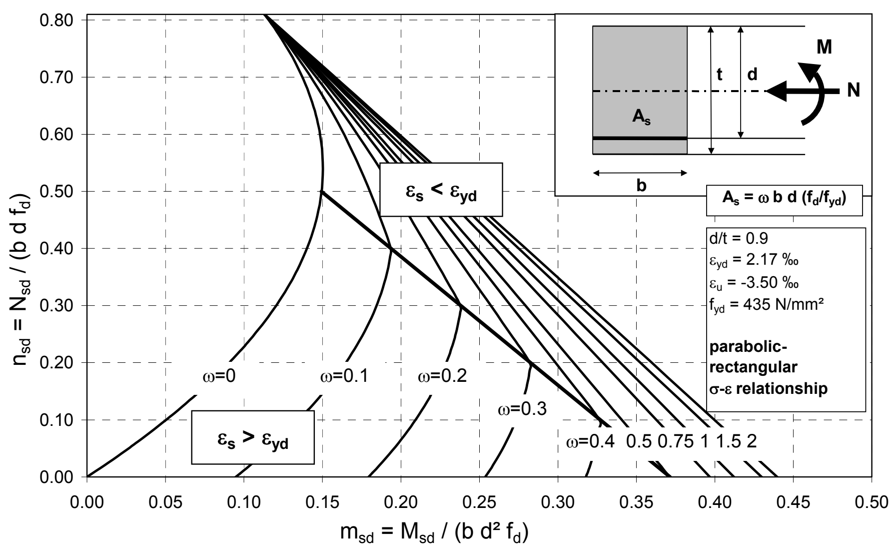

Figure 5 Design diagram for d/t=0.9 and parabolic-rectangular material behavior

4 Examples for the design of reinforced masonry structures

4.1 Reinforced masonry beam

In view of an easy application of the new concept for the dimensioning of the required reinforcement the masonry beam shown in Figure 6 is dimensioned. According to Eurocode 6 the required reinforcement is calculated on the basis of a linear, parabolic and parabolic-rectangular stress-strain relationship.

Masonry: e.g. vertically perforated clay brick with general purpose mortar
f_d = 1.9 MN/m²; t = 240 mm

Structural system: $l_{ef} \approx$ 2.35 m; $d \approx$ 0.40 m

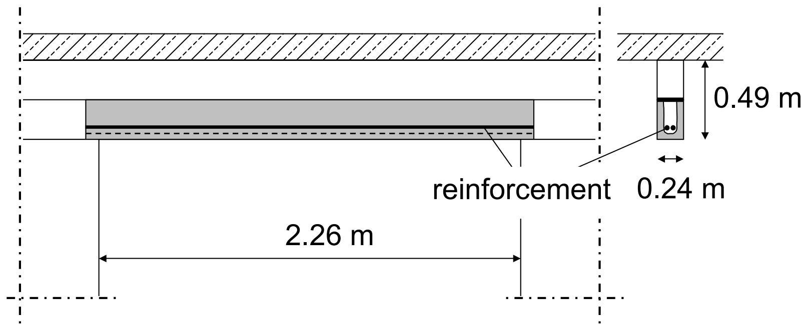

Figure 6 Masonry beam with horizontal reinforcement

Loads: g = 11.0 kN/m; q = 6.5 kN/m $\rightarrow$ M_{sd} = 17.0 kNm

$$\text{(9)} \qquad m_{sds} = \frac{M_{sds}}{b \cdot d^2 \cdot f_d} = \frac{0.0170}{0.24 \cdot 0.40^2 \cdot 1.9} = 0.233$$

Required reinforcement on the basis of linearly elastic material behavior:

$$\text{(15)} \qquad \overline{\omega} = 1 - \sqrt{1 - \frac{8}{3} \cdot m_{sds}} = 0.385 \qquad (\overline{\omega} > 1/3)$$

$$\text{(16),(17)} \quad \omega_1 = \frac{3}{4} \cdot \overline{\omega} = 0.289 \qquad \omega_2 = \frac{10 \cdot \overline{\omega}}{6 - 9 \cdot \overline{\omega}} \cdot \omega_1 = 0.439$$

$$\text{(11)} \qquad A_s = \omega_2 \cdot b \cdot d \cdot \frac{f_d}{f_{yd}} = 0.439 \cdot 0.24 \cdot 0.40 \cdot \frac{1.9}{435} \cdot 10^4 = \underline{1.84 \text{ cm}^2}$$

Required reinforcement on the basis of parabolic material behavior:

$$\text{(18)} \qquad \overline{\omega} = 1 - \sqrt{1 - 2.25 \cdot m_{sds}} = 0.310 \qquad (\overline{\omega} < 0.375)$$

$$\text{(19)} \qquad \omega_1 = \frac{8}{9} \cdot \overline{\omega} = 0.276$$

$$\text{(11)} \qquad A_s = \omega_1 \cdot b \cdot d \cdot \frac{f_d}{f_{yd}} = 0.276 \cdot 0.24 \cdot 0.40 \cdot \frac{1.9}{435} \cdot 10^4 = \underline{1.16 \text{ cm}^2}$$

Required reinforcement on the basis of parabolic-rectangular material behavior:

$$\text{(21)} \qquad \overline{\omega} = 1 - \sqrt{1 - 2 \cdot m_{sds}} = 0.269 \qquad (\overline{\omega} < 0.5)$$

$$\text{(22)} \qquad \omega_1 = \overline{\omega} = 0.269$$

$$\text{(11)} \qquad A_s = \omega_1 \cdot b \cdot d \cdot \frac{f_d}{f_{yd}} = 0.269 \cdot 0.24 \cdot 0.40 \cdot \frac{1.9}{435} \cdot 10^4 = \underline{1.13 \text{ cm}^2}$$

According to the presented masonry beam the required reinforcement depends on the stress-strain relationship of masonry and varies from A_s=1.13 cm² for parabolic-rectangular to A_s=1.84 cm² for linearly elastic material behavior. This wide range underlines the necessity of applying the new design method, which regards the material behavior of different masonry types.

4.2 Reinforced masonry basement wall

In order to clarify the application of the approximation method for lateral wall deformation according to theory of 2nd order a basement masonry wall with vertical

reinforcement is being designed, too. Hereby axial loads and lateral earth pressure have to be regarded. The basement wall which is illustrated in Figure 7 is vertically reinforced in the center of the wall.

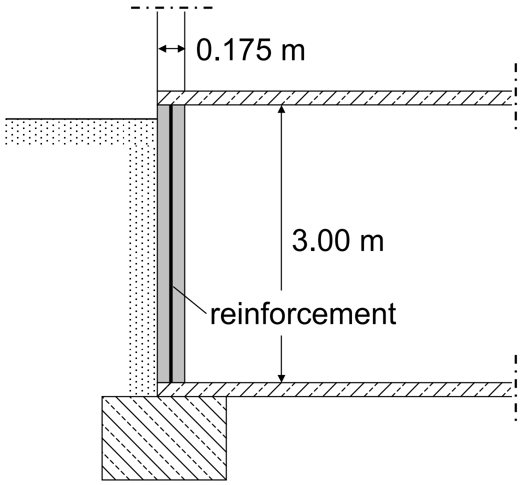

Figure 7 Reinforced masonry basement wall subjected to lateral earth pressure

Masonry:	e.g. vertically perforated calcium silicate brick with normal mortar f_d = 5.0 MN/m²; t=175 mm
Structural system:	h_{ef} = 3.00 m; d = 0.0875 m
Loads:	N_{sd} = 35.0 kN/m; M_{sd} = 7.0 kNm/m

Load eccentricity according to theory of 1st order: $e_I = \frac{M_{sd}}{N_{sd}} = 0.20 \text{ m}$

Load eccentricity according to geometrical imperfection: $e_a = \frac{h_{ef}}{450} = 0.0067 \text{ m}$

Additional load eccentricity according to theory of 2nd order:

(6) $$\Delta e_{II} = \frac{1}{2400} \cdot \frac{h_{ef}^2}{d} = 0.043 \text{ m}$$ (new method for $|\varepsilon_u|$=2,0‰)

(7) $$\Delta e_{II} = \frac{1}{1750} \cdot \frac{h_{ef}^2}{d} = 0.059 \text{ m}$$ (new method for $|\varepsilon_u|$=3,5‰)

(3) $$\Delta e_{II} = \frac{1}{2000} \cdot \frac{h_{ef}^2}{t} = 0.026 \text{ m}$$ (Eurocode 6)

(2) $$\Delta e_{II} = \frac{h_{ef}}{46} - \frac{t}{8} - e_a = 0.037 \text{ m}$$ (DIN 1053-3:1990)

The additional load eccentricity according to theory of 2nd order varies between Δe_{II}=0.026 m and Δe_{II}=0.059 m depending on the different material behavior and approximation methods. Due to the reinforcement built in the middle of the wall the effects according to theory of 2nd order are underestimated if the effective depth d is not considered. Consequently the total bending moment is being calculated on the basis of Equation (6):

$$e_{II} = e_I + e_a + \Delta e_{II,\, Eq.(6)} = 0.250 \text{ m} \quad \rightarrow \quad M_{sd,II} = 8.8 \text{ kNm/m}$$

Required reinforcement on the basis of parabolic material behavior:

$$n_{sd} = \frac{N_{sd}}{b \cdot d \cdot f_d} = \frac{0.035}{1.0 \cdot 0.0875 \cdot 5.00} = 0.080 \tag{8}$$

$$m_{sds} = \frac{M_{sd,II}}{b \cdot d^2 \cdot f_d} + n_{sd} \cdot \left(1 - \frac{t}{2 \cdot d}\right) = \frac{0.0088}{1.0 \cdot 0.0875^2 \cdot 5.0} = 0,230 \tag{9}$$

$$\overline{\omega} = 1 - \sqrt{1 - 2.25 \cdot m_{sds}} = 0.305 \tag{18}$$

$$\omega_1 = \frac{8}{9} \cdot \overline{\omega} - n_{sd} = 0.191 \tag{19}$$

$$A_s = \omega_1 \cdot b \cdot d \cdot \frac{f_d}{f_{yd}} = 0.191 \cdot 1.0 \cdot 0.0875 \cdot \frac{5.0}{435} \cdot 10^4 = \underline{1.92\ \text{cm}^2/\text{m}} \tag{11}$$

5 Conclusion

The design of a reinforced masonry wall with axial loads requires a structural analysis according to theory of 2nd order. In this context a new approximation method, which is based on the theoretical background of DIN 1045-1:2001 and Eurocode 2 for reinforced concrete has been developed. Hereby the varying material behavior of different masonry types and the effective depth is being regarded. The required reinforcement can be dimensioned on the basis of the total bending moment and the axial force with new simplified analytical equations. Accordingly the use of design diagrams and design tables is unnecessary in future. Due to the general formulation of the design equations any material behavior of masonry can be considered. Consequently the design method is more economic and transparent than the existing concepts. Furthermore the design of reinforced concrete and masonry is consistent, when using the new design method, because the different structural materials can be regarded by specific input parameters. The application of this new easy-to-use method is presented with the design of a reinforced masonry beam and a reinforced basement wall.

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